STEREOSCOPIC PIV MEASUREMENT IN LAMINAR ROTATING PLANE COUETTE FLOW

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Abstract Plane Couette flow with spanwise system rotation shows structures of streamwise-oriented roll cells that arise due to the instability by the Coriolis force when the system rotation is in the opposite direction to the mean flow vorticity. The momentum transport caused by such roll cell structures makes the flow tend to exhibit zero absolute vorticity. In the present study, stereoscopic PIV measurements in the rotating plane Couette flow were carried out in order to further illuminate the vortex structures and transport phenomena in this flow. The Reynolds stresses and some terms of its transport equation were evaluated to discuss the transport phenomena caused by the coherent structure. Furthermore, the wall shear stress was evaluated based on the measurement results of the Reynolds and viscous shear stresses and its variation with the system rotation rate is also presented.

INTRODUCTION

In a shear flow subject to system rotation where the axis of the system rotation is parallel to the mean flow vorticity, the Coriolis force has a remarkable effect on stability of the flow field depending on whether the system rotation has the same sign as the mean flow vorticity or not; in the cyclonic case, where the system rotation and the mean flow vorticity have the same sign, the Coriolis force effect stabilizes the flow, while in the anticyclonic case streamwise-oriented roll cells appear by the Coriolis-force-induced instability.

As another interesting aspect of rotating shear flows, it has been observed that the absolute vorticity, which is defined as the sum of the mean flow vorticity and the system rotation, tends to zero when the system rotation rate is high enough. Such mean flow behavior has been reported by earlier numerical simulations [1, 4, 5], and it has been suggested that the presence of the streamwise-oriented roll cells causes the zero-absolute-vorticity states.

The plane Couette flow with system rotation can be considered as a good test case to study the Coriolis force effect, because the plane Couette flow is conceptually the simplest wall shear flow both in laminar and turbulent flow regimes. Some experimental investigations have been reported so far including flow visualizations [3] and quantitative velocity measurement [2]. In particular, the zero-absolute-vorticity states have been observed in this flow for low Reynolds numbers [2].

In the present study, stereoscopic PIV measurement in a rotating laminar plane Couette flow is carried out using the same flow apparatus as those used in [2, 3]. In order to further investigate transport phenomena caused by the streamwise-oriented roll cells, the Reynolds shear stress and some terms of its transport equation are investigated.

EXPERIMENTAL SETUP AND PRELIMINARY RESULTS

The experiments were undertaken using a unique apparatus at KTH, in which a whole facility of plane Couette flow is mounted on a turntable and thus can be rotated. The stereoscopic PIV system consisted of a continuous laser, two CCD cameras with tilt lenses and a water prism and was also fixed on the turntable with the plane Couette flow facility as

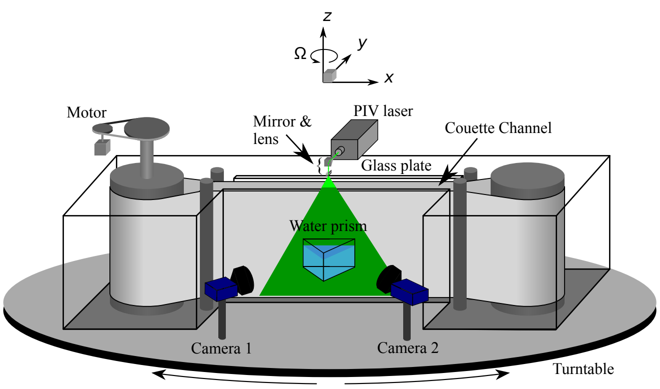

Figure 1. Rotating Couette flow apparatus with stereoscopic PIV setup.

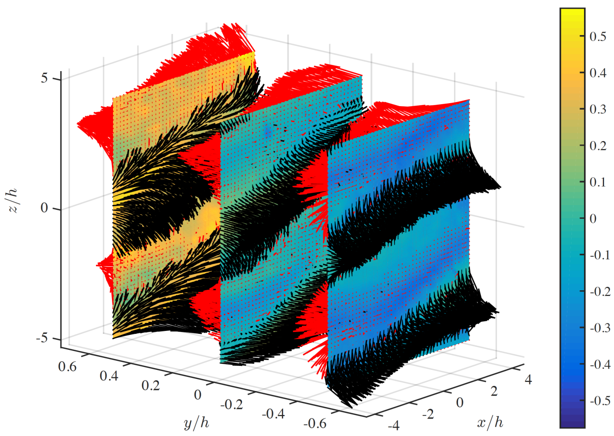

Figure 2. Instantaneous velocity distribution at $\mathrm{Re} = 100$ and $\Omega = 8$. The color indicates u and the red/black arrows represent velocity vectors with positive/negative v.

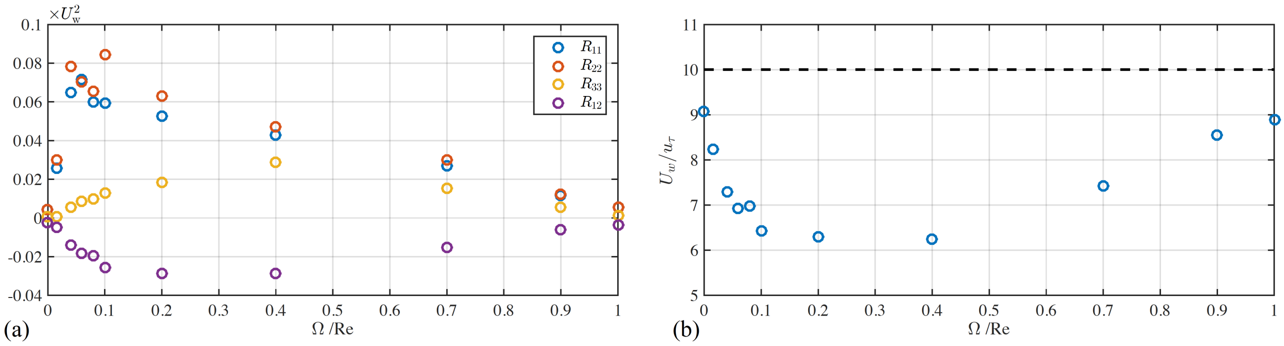

Figure 3. Statistical quantities at various rotation numbers: (a) Integrated Reynolds stresses $R_{ij} = \int_{-h}^{h} \langle u_i' u_j' \rangle dy$ scaled by hU_w^2, (b) ratio between the velocity scales U_w/u_τ with the rotation number (the dashed line indicates the theoretical value at the no rotation case, $U_\mathrm{w}/u_\tau = \mathrm{Re}^{0.5}$).

schematically shown in Fig. 1. The measurement operation was remotely controlled via a wireless network connection from a stationary workstation. The coordinate system was defined such that the origin was fixed at the centre of the channel and x-, y- and z-axes were taken in the streamwise, wall-normal and spanwise directions. The laser sheet was arranged to be parallel to the x-z plane by a right-angle mirror and a cylindrical lens, and can be traversed in the y-direction by a motorized traverse unit, which enable us to do measurements at several different y-positions in a sequence.

The flow parameters to be considered are the Reynolds number $\mathrm{Re} = U_\mathrm{w} h/\nu$ and the rotation number $\Omega = 2\Omega_z h^2/\nu$, where U_w and $2h$ are the belt speed and the distance between the belts, respectively, Ω_z is the system rotation rate (rad/s) and ν is the kinematic viscosity. In the present measurement the belt speed U_w and the wall spacing $2h$ were 10.7 mm/s and 18.7 mm, respectively, and consequently the Reynolds number was 100. The turntable was rotated in the anticyclonic direction with a rotation rate of $0 \leq \Omega \leq 100$.

Figure 2 presents instantaneous velocity field measureds by the stereoscopic PIV at $\mathrm{Re} = 100$ and $\Omega = 8$ for $y/h = 0$ and ± 0.53. The color indicates the streamwise velocity u and the red/black arrows show velocity vectors with the positive/negative wall-normal velocity v. A wavy streamwise-oriented roll cell can be clearly observed with significant variation of the wall-normal velocity v.

Statistical quantities such as the mean velocity and the Reynolds stresses were evaluated by taking average in the x- and z-directions and in time. Figure 3a shows variations of the whole amount of the Reynolds stress existing in the channel, which was evaluated as $R_{ij} = \int_{-h}^{h} \langle u_i' u_j' \rangle dy$. It is shown that the Reynolds normal stresses R_{11} and R_{22} were of almost the same magnitude regardless the system rotation rate, while the spanwise normal stress R_{33} was much smaller than the others at a low rotation rate. The Reynolds shear stress R_{12} showed the largest magnitude at about $\Omega = 20$ - 40. Furthermore, in the plane Couette flow the total stress $\tau = \mu dU/dy - \rho \langle u'v' \rangle$ is constant across the channel and equal to the wall shear stress τ_w. Therefore, it is in principle possible to determine the friction velocity u_τ based on the measurement results. Figure 3b presents variation of the ratio between the velocity scales U_w/u_τ, which is theoretically equal to $\mathrm{Re}^{0.5}$ at $\Omega = 0$. It is shown that U_w/u_τ took the minimum near $\Omega = 20$ - 40, which indicates the significant momentum transport in the wall-normal direction by the roll cells at this rotation number.

SUMMARY AND OUTLOOK

In the present study, stereoscopic PIV measurements were carried out in laminar rotating plane Couette flow in order to further investigate the momentum transport caused by the streamwise-oriented roll cells. The change in the vortical structure in the flow field with the rotation number was investigated in terms of the Reynolds stresses, and the friction velocity was also indirectly evaluated based on the viscous and Reynolds shear stress profiles. In the presentation, we focus on the transport equation of the Reynolds stresses to further invesitgate the transport phenomena caused by the presence of the roll cells, and the mechanism of the zero-absolute-vorticity behavior will be discussed.

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